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RESEARCH ON MILLIMETER FERROMAGNETIC TYPE PARAMETRIC AMPLIFIER
(Unclassified)

Contract No. DA-36-039 SC 89071

Report No. 7

(Continuation of Contract No. DA-36-039 SC 87401)

Third Quarterly Progress Report

1 August 1962 to 31 October 1962

January 1963

Prepared for

U.S. ARMY SIGNAL RESEARCH AND DEVELOPMENT AGENCY
Fort Monmouth, New Jersey

By

WESTINGHOUSE ELECTRIC CORPORATION
Air Arm Division
Baltimore, Maryland

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The objective of this research program is to investigate the feasibility of achieving parametric amplification in the millimeter frequency region using a ferromagnetic material as the coupling element.

Prepared by:
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1. PURPOSE

This study ~~is~~ investigating techniques were continued for ferromagnetic parametric amplification in the millimeter-wave frequency region. Attention is being given to the improvement of the performance of discrete amplifiers. New ferromagnetic materials and new configurations particularly suited to millimeter-wave application are being investigated. Emphasis is being given to traveling-wave parametric amplification utilizing ferromagnetic propagation structures.

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2. ABSTRACT

In previous reports, the dispersion of four of the modes of the longitudinally magnetized ferrimagnetic rod has been presented for 8 mm and 4 mm, and $H < H_o$, where H_o is the magnetic field for gyromagnetic resonance. In this period, fairly good experimental correlation was obtained for the 8-mm data. ~~In addition,~~ new data ~~have been~~ was obtained for 2 mm, $H < H_o$, and for 8 mm, $H > H_o$. A method for establishing an operating point is described. ~~As an example,~~ a rod size is shown which will support three appropriately chosen simultaneous electromagnetic resonances.

Work has begun on the dielectric rod structure as a means of treating the more difficult case of the ferrite rod. ~~For example,~~ similar feeds are required for analogous modes. Analysis of the dispersive properties is much simpler and is available from a number of previous studies. An operating point is chosen from a knowledge of the dispersive behavior of the dielectric rod.

The magnetodynamic mode chart ~~discussed in the two previous reports~~ is ~~substantially~~ completed. Charting over a wide frequency range has permitted close correlation with the theoretical Walker mode spectrum at low frequencies and good agreement with predicted modes of the dielectric sphere resonator at high frequencies. This will allow positive mode identification, thereby augmenting the ferrimagnetic measurements capability.

3. PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

A conference was held at Fort Monmouth on 20 September 1962 between R. A. Moore of Westinghouse and John Carter of USASRDL to discuss progress on the contract.

On 17 October 1962, John Carter and Martin Auer visited Westinghouse to discuss with P. M. Pan and R. A. Moore the progress and obligations of the work. It was agreed that magnetodynamic structures should be emphasized.

4. FACTUAL DATA

4.1 FERRIMAGNETIC MAGNETODYNAMIC CONFIGURATION

A study of the dispersive properties of surface wave structures is continuing because of their capacity to concentrate fields for parametric interaction. Of particular interest is the much larger effective filling factor obtained on the surface wave structure. By making the length of the rod equal to an integral number of half-wavelengths of a microwave signal, a resonant structure is formed which can be tightly coupled to the signal.

The study has been directed toward the investigation of longitudinally magnetized ferrimagnetic rod structures. Obtaining appropriate simultaneous resonances (signal, idler, and pump) on a single rod would be difficult for a structure with a resonant mechanism as complicated as the ferrimagnetic rod. For this reason, an analysis has been conducted of the dispersive properties of the infinite rod propagation structure. The characteristic equation has been evaluated by digital computer for several of the lowest order modes. These will have the simplest field structure and the greatest likelihood of being suitable for parametric interaction. The modes are designated by two digits, (n, m), where n refers to the number of field variations in the circumferential direction, and m indicates the radial direction dependence. In previous reports, the calculated dispersive characteristics of the two (0, 1) modes, the (1, 1) mode, and the (-1, 1) mode have been presented for 8 mm and 4 mm, and $H < H_o$ where H_o is the magnetic field for gyromagnetic resonance. Some experimental correlation has also been presented.

4.1.1 Dispersive Data at 8 MM and 2 MM

In Report No. 5, 8-mm dispersive data were presented for a wide range of magnetic fields, that is, from 4 kiloersteds up to negative permeability.

Coming from the computer, the data are presented as $\frac{\lambda_g}{\lambda_o}$ vs $\frac{2\pi r_o}{\lambda_o}$ for the particular values of frequency, f_o, the magnetic field, H, and the mode, (n, m), where λ_o and λ_g are, respectively, the free space wavelength and waveguide wavelength of the signal, and r_o is the radius of the rod. By defining an integer k, where

$$k \frac{\lambda_g}{2} = h = \text{height of rod}$$

it is possible to present the data in the form f_o versus H, for specific values of r_o and (n, m, k). The theoretical data are extensive enough to compute the frequency behavior of the first three multiples of each of the four modes being studied; i.e., for k = 1, 2, 3. However, since the modes depend critically on the rod diameter, not all of the modes will have resonances in a particular experimental range of conditions.

The 8-mm dispersive data have been tested experimentally on rods composed of R-1 material ground to 100 mil, 125 mil, and 150 mil diameters and inserted across the narrow dimension of K_a-band waveguide so that the broad dimensions served as the conducting end plates of the cavity.

In figures 1 and 2 experimental modes were found which correlated quite well with theoretical calculations. The other experimental curves which occur in the figures are probably due to higher order modes. It should be noted that the resonances tend to fall into two groups depending on the degree of variation of resonant frequency with the changing field. As discussed in previous reports, the degree of dependence of the dispersion on the magnetic field suggests the degree of coupling with the gyrating magnetic moment. A strong dispersion dependence suggests that the mode is positively circularly polarized with respect to the RF magnetic field. Weak dependence suggests negative circular polarization or longitudinal fields.

That the resonances do not actually cross in figures 1 and 2 is due to weak coupling between the respective modes. The apparent lack of correlation for the structure shown in figure 3 will require further study. The large number of modes present significantly complicates correlation with the theoretical curves.

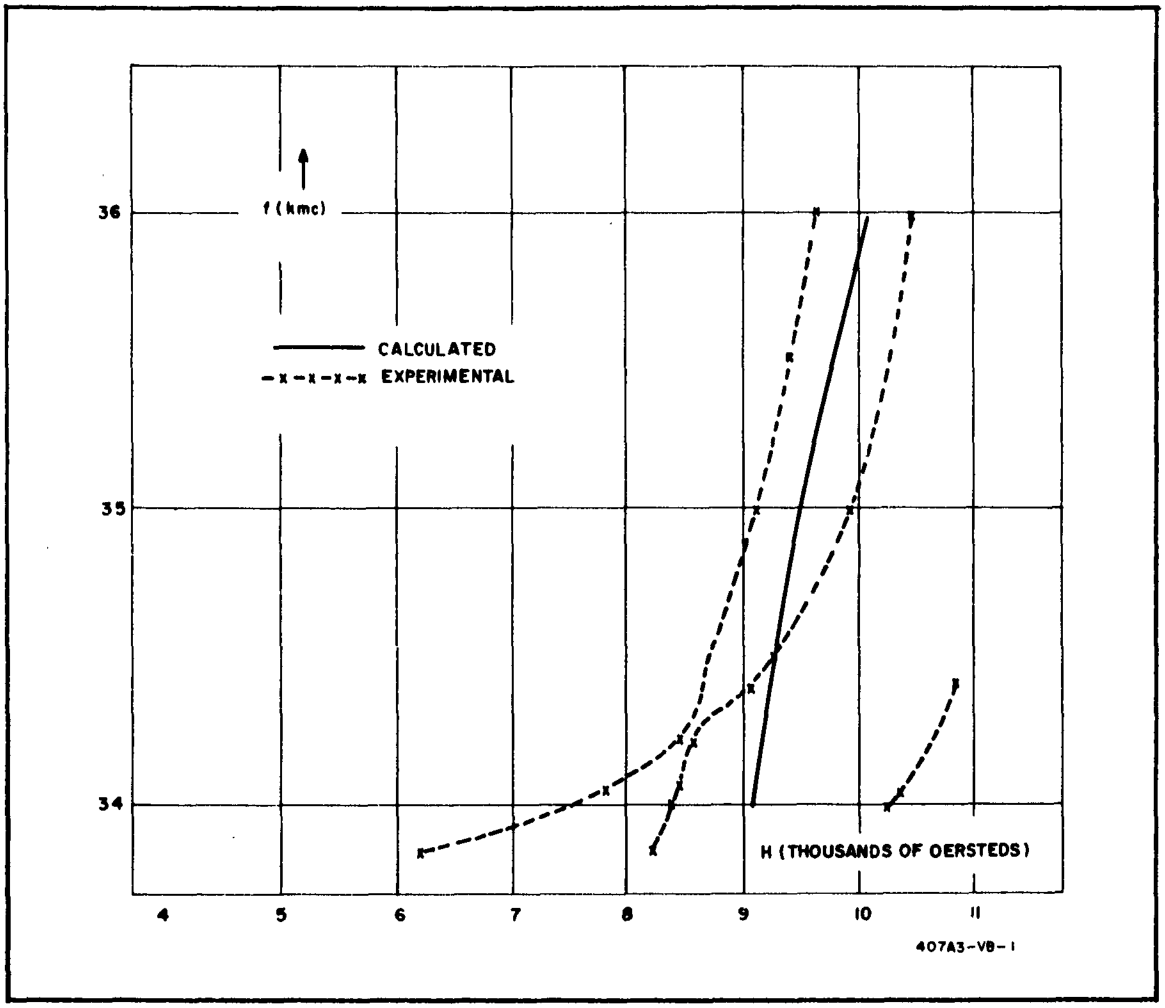

Figure 1. K_a-Band Experimental Correlation of (-1, 1, 1) Mode on 100-Mil Diameter R-1 Rod

New data have been calculated for 8 mm and 2 mm. The 8-mm data are computed for $H > H_o$ in order to have data at the same d-c magnetic fields as the 4-mm data presented in Report No. 6. Data typical of the results are shown in paragraph 4.1.2 where a sample operating point is determined.

In figure 4, the 2-mm data are presented. Only the (0, 1) mode, S_1 cutoff, is included since it is the most suitable as a pump mode; this will be discussed later. There is so little variation of dispersive characteristics over the frequency range (f = 136, 138, 140 kilomegacycles) that this graph is suitable for the whole range. There is also decreasing variation with respect to

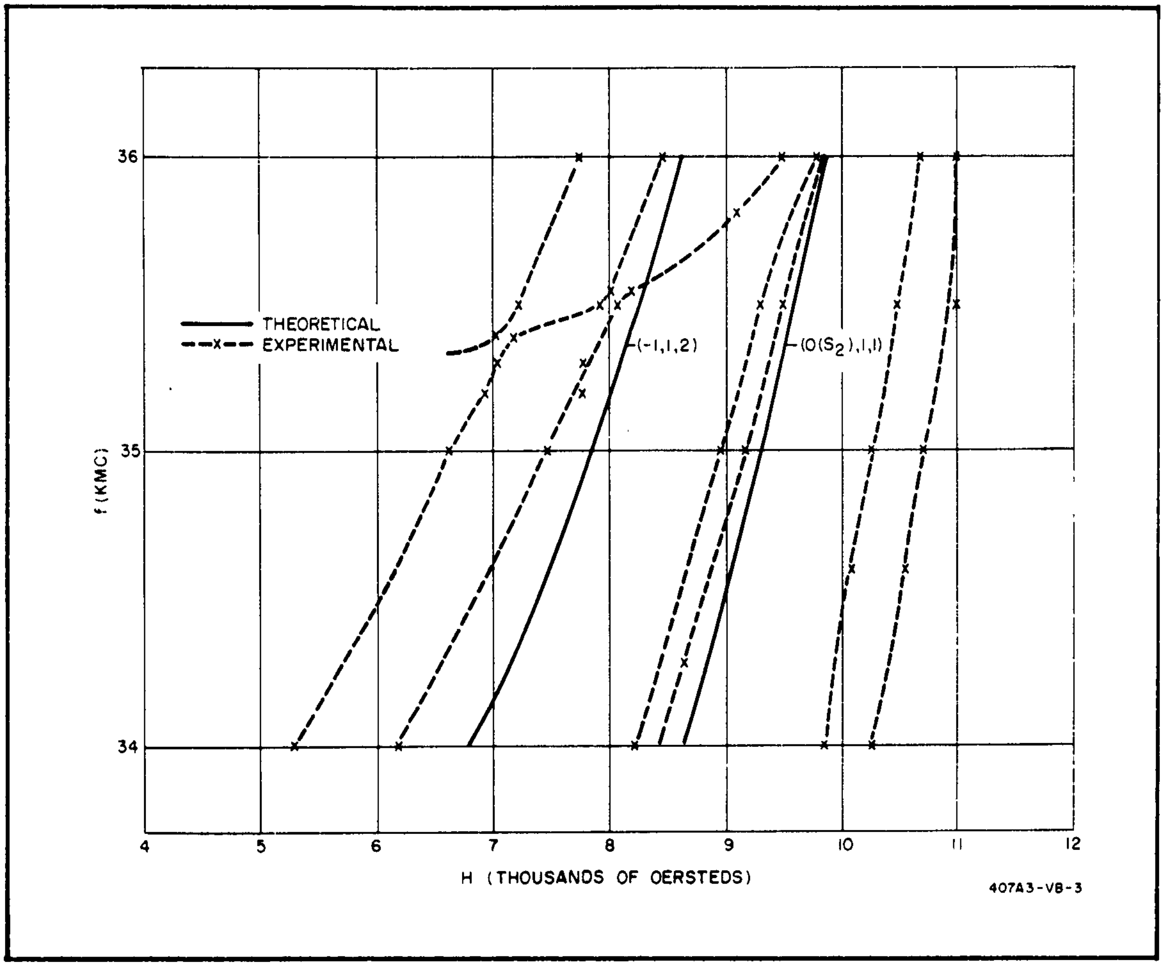

Figure 2. K_a-Band Experimental Correlation of Computed Modes on 150-Mil Diameter R-1 Rod

magnetic field as the fields fall farther below gyromagnetic resonance (H_o = 49 kiloersteds; H = 30, 26, 18, 10 kiloersteds). The limit of these curves is the better-known dispersive behavior of a nonmagnetic dielectric rod structure.

4.1.2 Dispersive Operating Point

The characteristic equation is being studied in order to find appropriate simultaneous resonances on a single ferrimagnetic rod structure. The computed data at 8 mm and 4 mm are sufficient to demonstrate how the data can be used to find such an operating point. Because the rod is, in effect, a periodic traveling-wave structure, certain results of traveling-wave amplifier

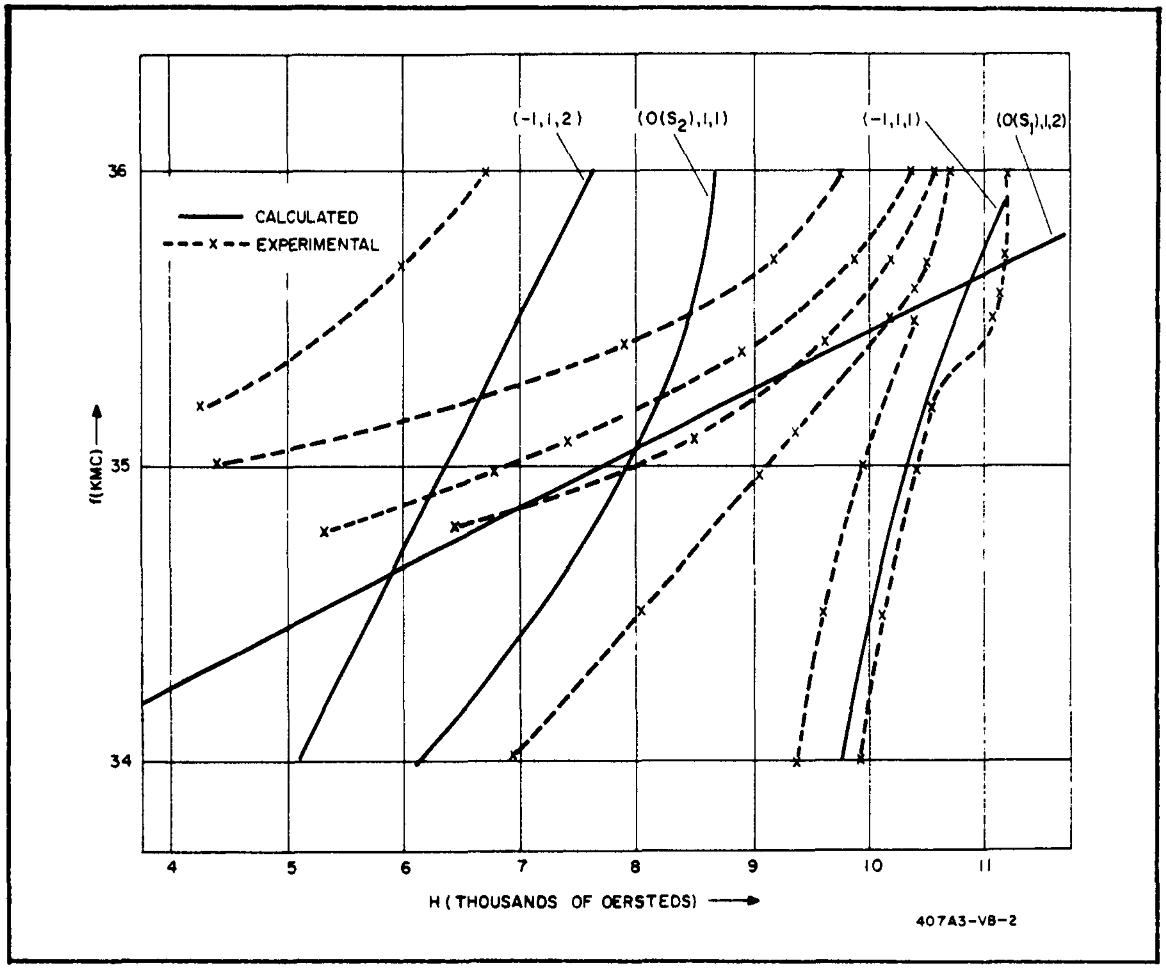

Figure 3. K_a-Band Experimental Correlation of Computed Modes on a 125-Mil Diameter R-1 Rod

analyses can be adopted immediately. In particular, the requirement that

$$\beta_s + \beta_i = \beta_p$$

(where β is the wave number and the subscripts represent signal, idler, and pump), can be used along with the relation

$$f_s + f_i = f_p$$

to establish the requirement for an operating point that

$$k_s + k_i = k_p$$

where k is once again the integer number of half-wavelengths on the length of the rod.

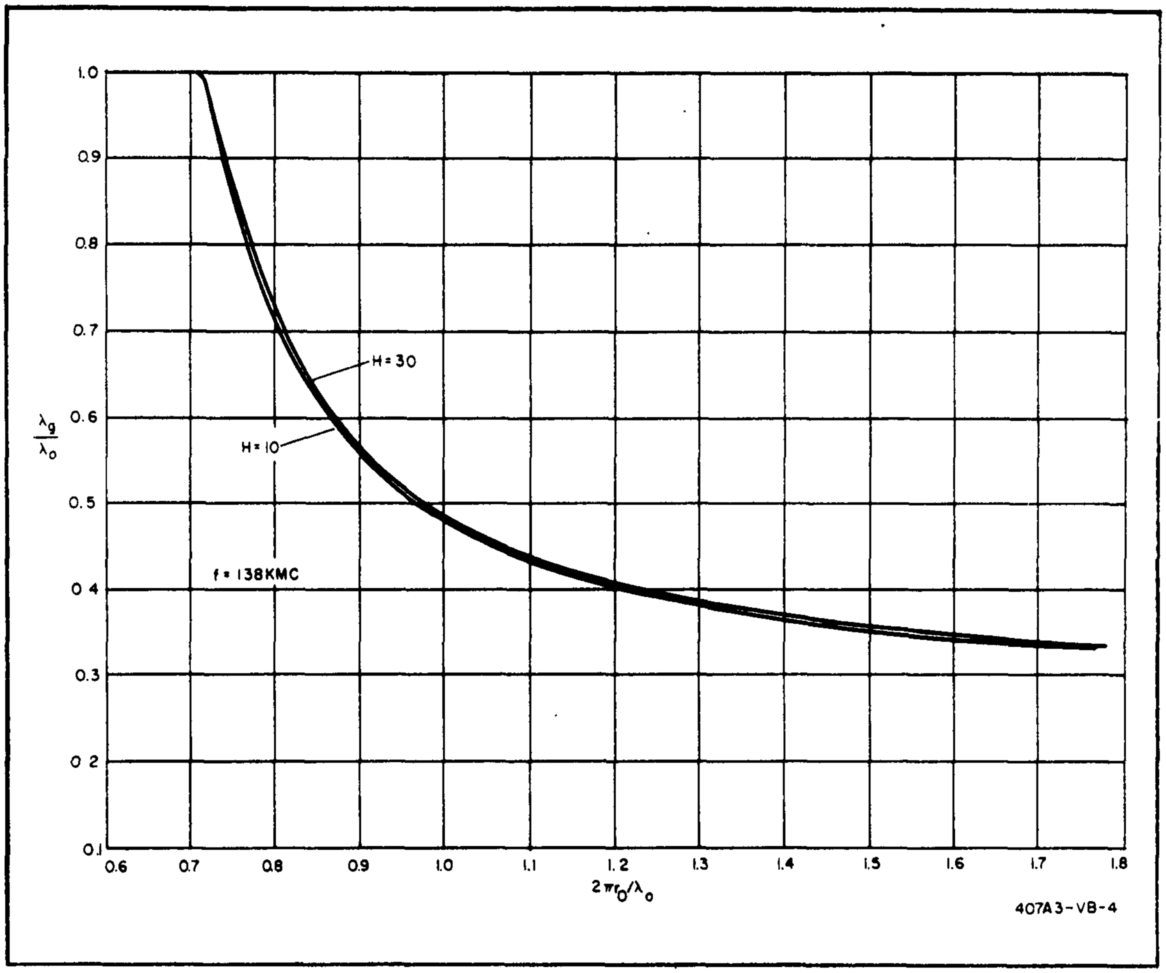

Figure 4. Two-Millimeter Dispersive Characteristics For the (0, 1) Mode, S_1 Cutoff, on R-1 Ferrite Rod

Because of the many variables ($f_{s,i,p}$, H, r_o, h, and the indices n, m, k) which must simultaneously be chosen to establish an operating point, a procedure which establishes limits on the simultaneous resonance of suitable modes must be used. Two such procedures have been found to be useful. Their application will be illustrated for the pump at 4 millimeters and the signal and idler at 8 millimeters. The zero order mode (0, 1) corresponding to S_1 will be used for the pump frequency. This is the circumferentially symmetric mode for which the variation of dispersion with d-c magnetic field is slight, suggesting a large parallel RF magnetic field component.

The (± 1, 1) modes which are analogous to the dielectric HE_{11} rod modes will be utilized for the signal and idler. The transverse field components of these modes are oppositely rotating circularly polarized as is required for a parametric interaction.

In the more general scheme, the dispersive data are utilized in the form of a plot of λ_g/λ_o versus $2\pi r_o/\lambda_o$ for each mode with the magnetic field as a parameter. It is necessary that the signal and idler modes be resonant for identical dimensions and for the same d-c magnetic field. To obtain coincident operating conditions, the plots of λ_g/λ_o versus $2\pi r_o/\lambda_o$ for the signal and idler modes can be plotted on the same chart keeping in mind the data must be normalized relative to a common free space wavelength λ_o. When this is carried out, a series of common operating points are obtained represented by the crossover points of the d-c magnetic field bias parameters. The curve of coincident operation of the two modes is obtained by connecting these points. A suitable operating point is thus obtained by superimposing the equivalent characteristics (λ_g/λ_o versus $\frac{2\pi r_o}{\lambda_o}$) for the pump mode (normalized with respect to the common free space wavelength) over this characteristic. The crossover point represents an operating point. This technique is particularly suitable for determining a useful range of operating points.

A procedure which is useful for finding the exact operating point when a range of possible operating points is known is demonstrated in figures 5 and 6.

As an example, suppose one examines λ_g/λ_o versus $\frac{2\pi r_o}{\lambda_o}$ graphs for the three chosen modes, with reference to feasible values for the λ_g's. By noting the range of diameters for all possible combinations of k's (subject to $k_s + k_i = k_p$), it appears that

$$k_s = 1, \ k_i = 2, \ k_p = 3$$

offers a good chance of obtaining simultaneous resonances on a single rod of about 100 mils in height. The (2, 2, 4) combination is also promising and will be investigated in the future.

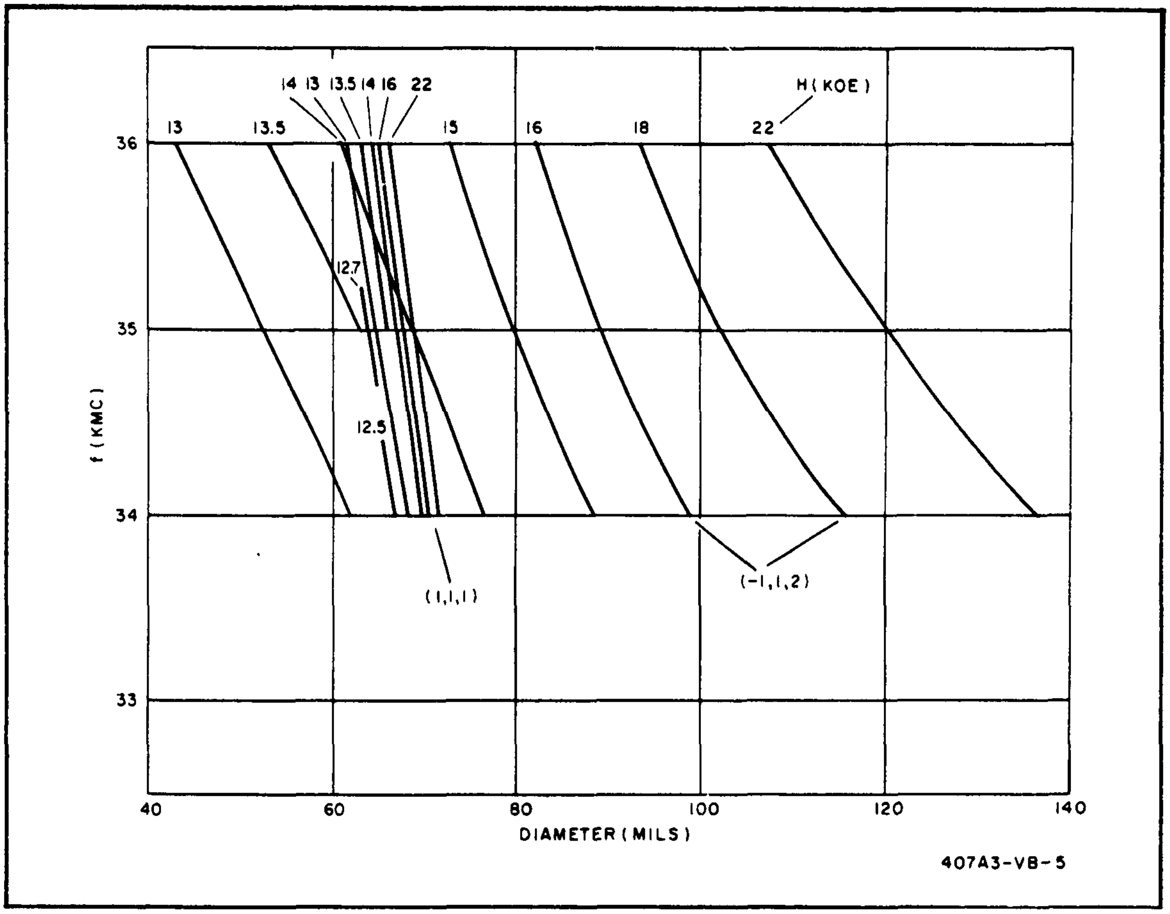

Figure 5. Signal, Idler Conditions on Operating Point

Convenient graphs of frequency versus diameter can be drawn for various values of magnetic field. Figure 5 presents the f, H, r_o curves for the two transverse modes. By summing the two frequencies at a given value of magnetic field, a value of $(f_s + f_i)$ is obtained as a function of diameter. This is plotted in figure 6 along with the pump mode frequency. Intersections of equal magnetic-field curves define operating points. It is apparent that one such point exists for approximately the values,

H	= 13.3 koe	
D_0	= 62 miis	
f_s	= 36.1 kmc	(1, 1, 1) mode
f_i	= 34.7 kmc	(-1, 1, 2) mode
f_p	= 70.8 kmc	(0 (S_1), 1, 3) mode

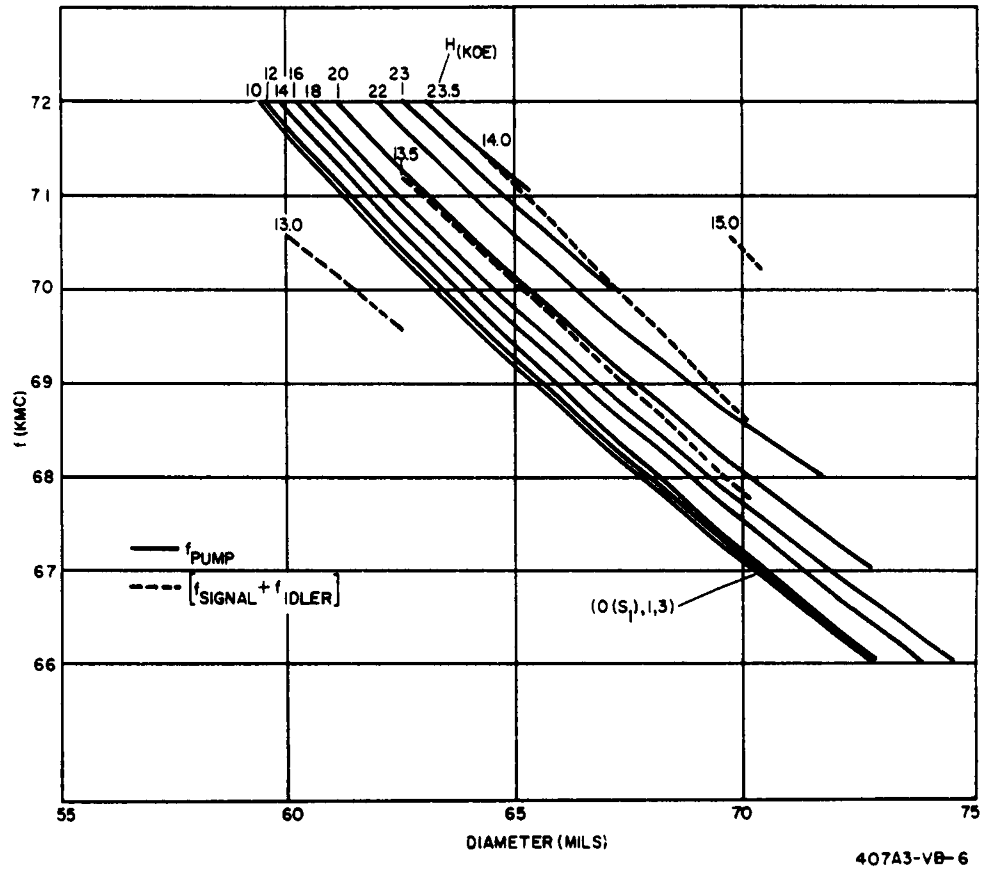

Figure 6. Pump Condition on Operating Point

This example is illustrative of the way in which operating points may be found from a knowledge of the solutions of the characteristic equation.

Progress has been made toward working out suitable resonance combinations for parametric operation; i.e., simultaneous resonance in three modes such that $f_1 + f_2 = f_3$ where the RF magnetic field of f_3 is parallel and those for f_1 and f_2 are transverse and oppositely rotating. These were demonstrated in the previous paragraphs. As has been suggested, because the structure is in reality a periodic traveling-wave structure, much insight can be obtained by virtue of the study of traveling-wave amplification discussed later in this report. Up to this point, the study of traveling-wave parametric amplification has concentrated primarily on operating points for which the signal and idler are different from resonance. These results show that a very large pump field would be necessary to operate with no signal biased at a material resonance. This analysis is being extended to include resonance and will be used to provide guide lines for establishing the parametric operating conditions for this structure.

Currently, data for the signal and idler have been calculated only for frequencies near 1/2 f_p where fundamental energy has been available. Now that other frequencies are being experimentally produced by harmonic generation, a wider range of possibilities for $f_{s,i,p}$ is available. Additional data will be computed as the traveling-wave study suggests more appropriate operating points.

4.1.3 Dielectric Rod Structure

Although the ferrite rod structure was selected for study to provide a maximum filling factor, it would appear that several problems still must be solved before it can be made into a practical amplifier. One of these is to determine a suitable operating condition. It will also be necessary to obtain, polish, and shape suitably large single crystals from which the structure can be constructed. In the meantime, a number of practical problems centering around the use of a surface wave resonant structure can be studied by experimentation on a similarly shaped dielectric structure. For example, for analogous modes similar feeds can be used. Further, analysis of the dispersive properties is much simpler and is available from a number of previous studies.

As an interim structure, the dielectric rod will be utilized as a resonant structure to support a parametric interaction. If a dielectric rod propagation structure is intersected by conducting planes separated by an integral multiple of half wavelengths, the structure is resonant. By the use of two or more propagation modes the structure can be made to resonate at more than one frequency. Subsequently, it will be shown that it is possible to design the dielectric resonant structure so that their resonant frequencies are suitably related for parametric amplification. A highly polished single crystal YIG resonator can be used as the active medium. This provides a much greater filling factor than is possible in the metallic cavity provided the resonator diameter is approximately equal to the diameter of the rod.

The initial investigation will be directed toward parallel pumped operation. This is also the mode of operation being investigated for the ferrite rod structure. To obtain circularly polarized signal and idler fields, these modes must resonate transversely to the axis of the dielectric rod. Thus, magnetostatic or electromagnetic modes with transverse RF magnetic fields must be used. An example of the latter would include the HE_{11} dielectric hybrid mode. To supply a pump field parallel to the rod axis, the H_{01} mode can be used.

Magnetostatic mode resonances could be used to support both the signal and idler. This would require that the pump frequency be the second harmonic of a frequency in the magnetostatic mode spectrum. As has been shown by a number of workers, this arrangement is very conducive to the generation of unstable spin wave modes. To reduce this tendency, an electromagnetic mode, well separated from the magnetostatic mode spectrum will be used to support either the signal or the idler and the material resonance (uniform precessional mode) to support the other. The HE_{11} mode will be utilized as the electromagnetic mode. In the following paragraphs, suitable dispersive relations will be determined to permit the simultaneous resonance of the HE_{11} and H_{01} modes for a parametric interaction. The uniform precessional mode is then tuned by the magnitude of the d-c magnetic field.

Figure 7 presents dispersive data for $\epsilon_r = 13.5$ in the form λ_g/λ_o versus r_o/λ_o for these two modes. They were calculated from characteristic equations involving the separation constants of the modes. More complete calculation would show that the HE_{11} mode asymptotes at both ends of the curve, to free space as $\frac{r_o}{\lambda_o} \ll 1$ and to the infinite dielectric medium as $\frac{r_o}{\lambda_o} \gg 1$.

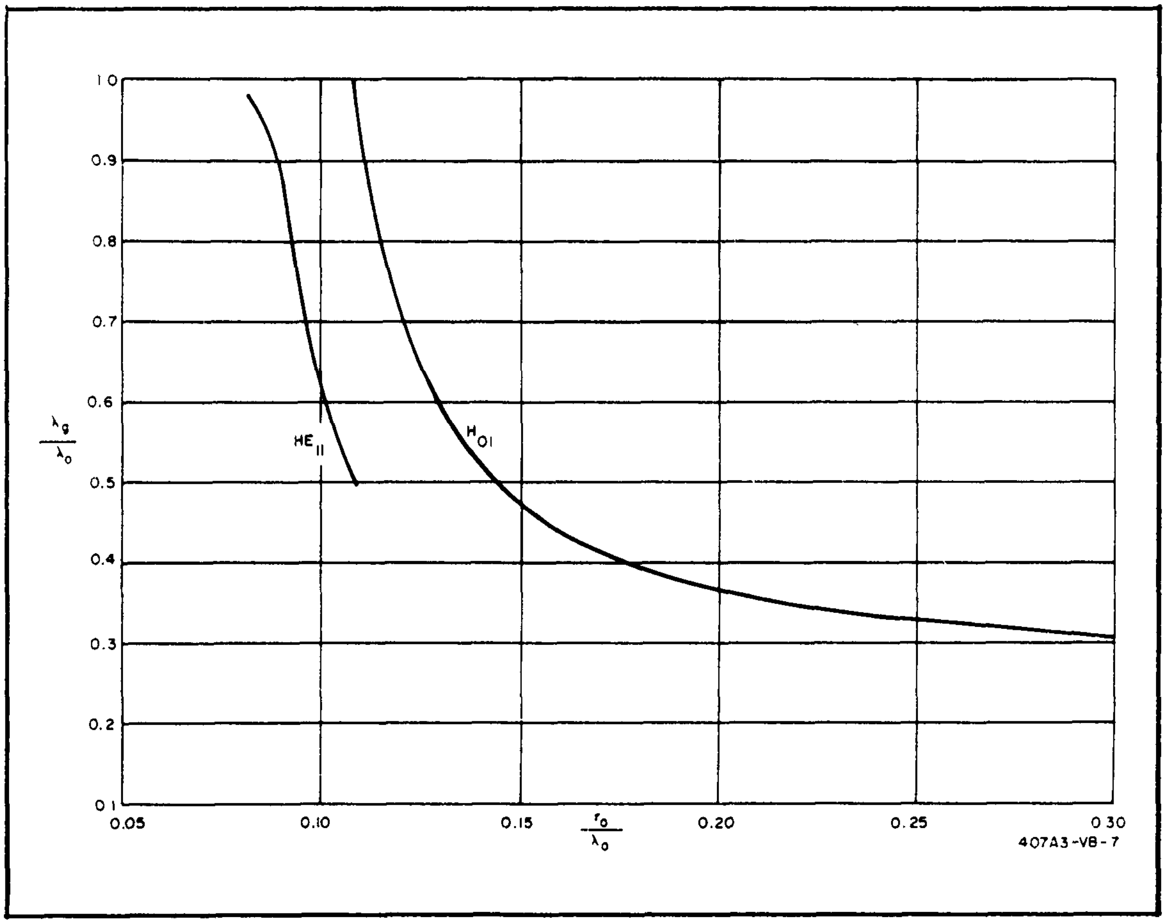

Figure 7. Dispersive Characteristics of Dielectric Rod Structure, $\epsilon_r = 13.5$

To determine suitable operating points, it is most convenient to make the following two adjustments.

a. The coordinates are independently normalized with respect to λ_{op} and λ_{ot}, the free space wavelength of the pump and either of the transverse modes. The wavelength λ_{op} has been arbitrarily chosen as the single normalizing factor and

$$\lambda_{ot} = 1/\sigma \; \lambda_{op} \qquad o < \sigma < 1$$

corresponding to

$$f_t = \sigma f_p$$

b. The longitudinal order of the modes must be established. Values of $k_t = 2$, $k_p = 3$ appear most suitable of the low order modes which have the proper fields at the ferrite sphere. Using the coordinate transformation equations:

$$\left(\frac{h}{\lambda_{op}}\right) = \frac{k_t}{2\sigma}\left(\frac{\lambda_{gt}}{\lambda_{ot}}\right) = \frac{k_p}{2}\left(\frac{\lambda_{gp}}{\lambda_{op}}\right)$$

and

$$\left(\frac{r_o}{\lambda_{op}}\right) = 1/\sigma\left(\frac{r_o}{\lambda_{ot}}\right) = \left(\frac{r_o}{\lambda_{op}}\right)$$

the results are plotted in figure 8. A region is thereby defined in which operating points exist. Two points exist for the condition $\sigma = 0.72$. As an example, if the pump mode is assumed to be at 4 mm, then the lower intersection implies

f_p = 69.1 kmc
f_t = 49.8 kmc
f_t' = 19.3 kmc
h = 0.124 inch
r_o = 0.0253 inch

Thus, this configuration would amplify a 50-kilomegacycle signal for which the idler resonance, f_t', could be a gyromagnetic resonance at $H \cong 7$ kilo-ersteds.

Excitation of dielectric rod resonant structures can be accomplished, for example, by means of suitable irises through one of the conducting planes at the end. Considerable effort in this direction has been carried out by Beam, et. al[1/]. In their analysis of the dielectric rod structure, these workers describe techniques for resonant cavity excitation to carry out dielectric constant and loss tangent measurements. A major effort in the

Reference 1. Beam, R. E., W. L. Firestone, D. G. Harman, W. A. Hughes, D. L. Margerum, R. A. Woodson, "Investigations of Multimode Propagation in Waveguides and Microwave Optics," Contract No. W 36 039 SC38240, Second Quarterly Report, 31 October 1949, Northwestern University, Evanston, Illinois.

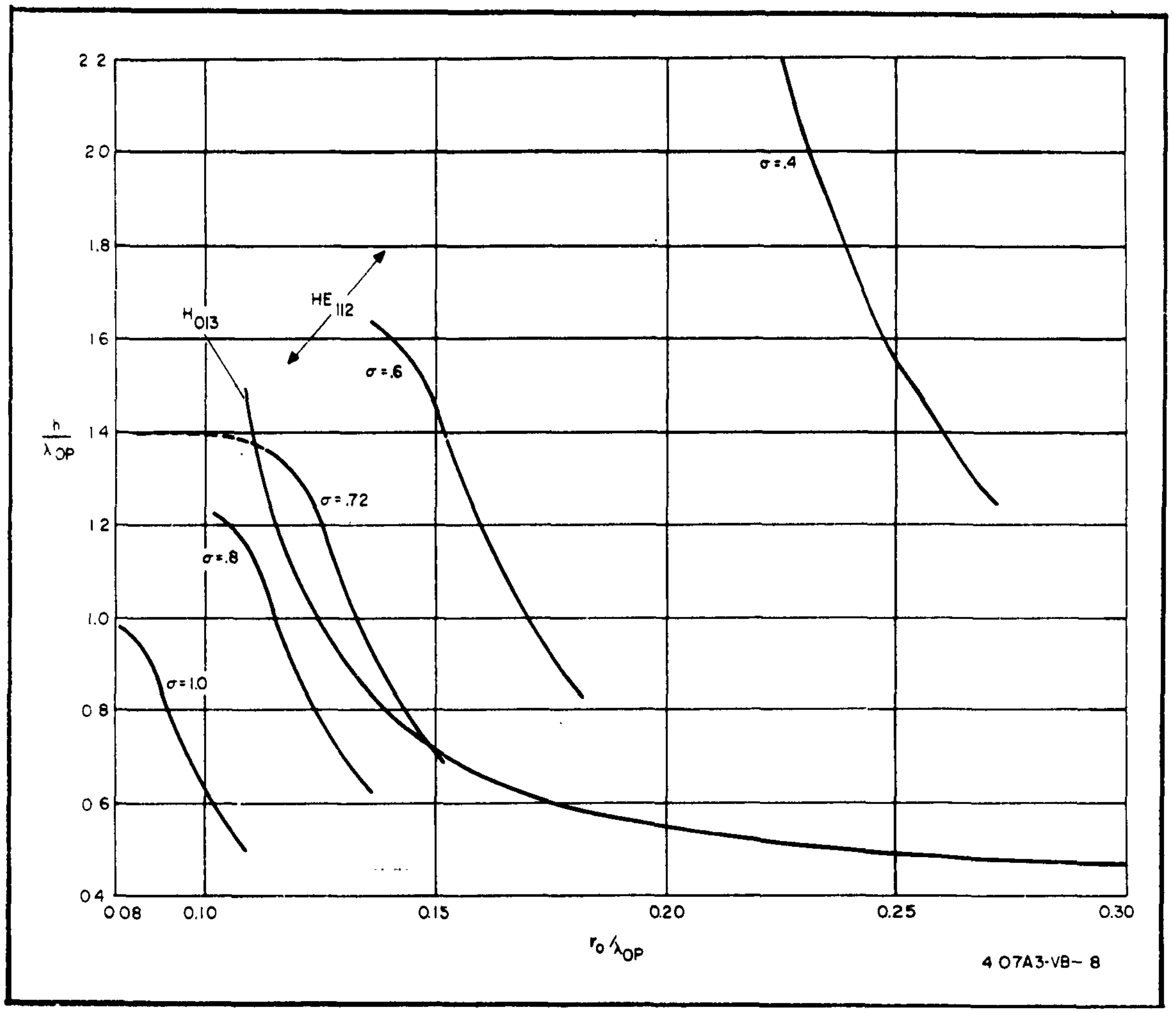

Figure 8. Adjusted Dispersive Characteristics of Dielectric Rod Structure, $\epsilon_r = 13.5$

following period will be to derive suitable simultaneous excitation for the pump and signal modes. Tests will be conducted on the structure excited in the signal and pump individually after which it will be tested as an amplifier.

4.2 TRAVELING-WAVE PARAMETRIC INTERACTIONS

In the previous quarterly report an expression for nonresonant traveling-wave amplification was developed analytically and a numerical example was presented. A more complete evaluation of this case is presented in table 1.

The important parameters are varied in order to determine their effect upon the threshold of gain. The threshold field is derived from the relationship

$$\gamma\ h_p > \sqrt{\left[\frac{\gamma\Delta H}{2} + \phi\,(\omega_o - \omega_1)\,\left(1 + \frac{\omega_o - \omega_1}{\omega_m}\right)\right]\left[\frac{\gamma\Delta H}{2} + \phi\,(\omega_o + \omega_2)\,\left(1 + \frac{\omega_o + \omega_2}{\omega_m}\right)\right]} \quad (1)$$

where ω_1 is positively circularly polarized and ω_2 is negatively circularly polarized. Thus, although $\omega_2 = \omega_o$, it will not experience resonance.

TABLE 1

DEPENDENCE OF THE THRESHOLD FIELD UPON MATERIAL PARAMETERS AND OPERATING CONDITIONS

Case	ΔH oer.	ϕ	f_o kmc	f_1 kmc	f_2 kmc	$4\pi M$ oer.	h_p oer (threshold)
I	10	0.001	70	67	70	1800	100
II	5	0.001	70	67	70	1800	77
III	10	0.002	70	67	70	1800	150
IV	10	0.001	70	80	70	1800	114
V	10	0.001	70	67	30	1800	74
VI	10	0.001	70	67	70	2700	83
VII	4	0.001	23	20	70	1800	47

The following general conclusions can be drawn from these results. The threshold is critically dependent upon magnetic linewidth and dielectric loss tangent. A comparison of Cases I, II, and III indicates that at the high frequencies being considered, dielectric losses dominate. Because the unperturbed fields are rapidly attenuated in the negative permeability region, operation here is impractical. Thus, to operate at the high frequency side of resonance at a point where the present analysis is valid, one must operate far enough from resonance to be out of this region. This results in poorer performance than is attained at the low frequency side of resonance.

Increasing the saturation magnetization will result in a lowering of the threshold, but as Case VI indicates, it is not an effective way of accomplishing this.

The best means of achieving a low threshold is by operating the idler in a positively circularly polarized mode near gyromagnetic resonance. By selecting this frequency much lower than the signal frequency (Case VII) both dielectric losses and magnetic losses can be minimized. The effectiveness in reducing dielectric losses can be seen from equation 1. Magnetic losses decrease because of a reduction in linewidth at the lower frequency.

It should be pointed out, however, that these operating conditions are not desirable for low noise operation. This requires that the idler frequency exceed that of the signal. As was indicated in the previous quarterly report, even under optimum operating conditions, pump field requirements are prohibitive.

Work has been proceeding on an analysis of traveling-wave parametric interaction where the signal (or idler) is at ferromagnetic resonance. When one of the interacting energies is at ferromagnetic resonance, the analysis becomes much more complicated. This complication arises because assumptions made in the present analysis are no longer valid so that the present perturbation analysis on an infinite medium propagation structure is no longer valid. Attempts are being made to devise a more rigorous approach.

An alternate approach to obtain an indication of the performance of parallel pumped traveling-wave interactions where one interacting signal is at ferromagnetic resonance is now underway. In this approach the ferrite forms only a portion of the cross section of the propagation structure. It now appears that this will allow sufficient simplification to carry through the analysis. This analysis, though underway, is incomplete at this time. It is expected that the analysis should be sufficiently far along to describe in detail in the next report.

4.3 MAGNETODYNAMIC MODE CHART

To facilitate ferrite properties measurements and to help understand the influence of electromagnetic propagation on ferrimagnetic resonance, a chart of the magnetodynamic mode dispersion of a spherical YIG resonator was arrived at experimentally (see figure 9). The chart was extended over a wide frequency range that permitted close correlation with Walker's[2/] results at low frequencies, and good agreement with predicted modes of the dielectric sphere resonator at high frequencies. As described in the first quarterly report, Walker[2/] plotted $\frac{\frac{\omega}{\gamma} - H_i}{4\pi M}$ versus $\frac{H_i}{4\pi M}$ to display his magnetostatic mode spectrum that was arrived at analytically by disregarding propagation effects. Having identified some of the modes as "Walker" modes, it can be seen that propagation effects become appreciable at about 6 kilomegacycles and that approaching dielectric resonance, the "Walker" modes asymptote to the constant frequency lines corresponding to modes of the dielectric resonator. During the study, it was observed that the coupling between the Walker modes and the dielectric modes varied widely. Certain modes, including the uniform precessional, decreased in reaction near dielectric resonance, certain others, however, increased in reaction thus complicating the spectrum and hampering measurements of linewidth and susceptibility. This phenomenon also made it difficult to chart all the observed modes over the entire range as the reaction became very small. Data to complete some of these modes are now being taken.

The dielectric sphere dispersion was arrived at by carrying out a perturbation analysis to the second order on the transcendental equation:

$$\frac{\left[NP\, j_n(NP)\right]'}{j_n(NP)} = \frac{\left[P\, h_n(P)\right]'}{h_n(P)} \quad {}^{3/}$$

Reference 2. Walker, L. R., "Magnetostatic Modes in Ferromagnetic Resonance," Phys. Rev., Vol. 105, January 1957, pp. 390-399.
Reference 3. Stratton, J. A., Electromagnetic Theory, McGraw-Hill Book Co., Inc., New York 1941, p. 557.

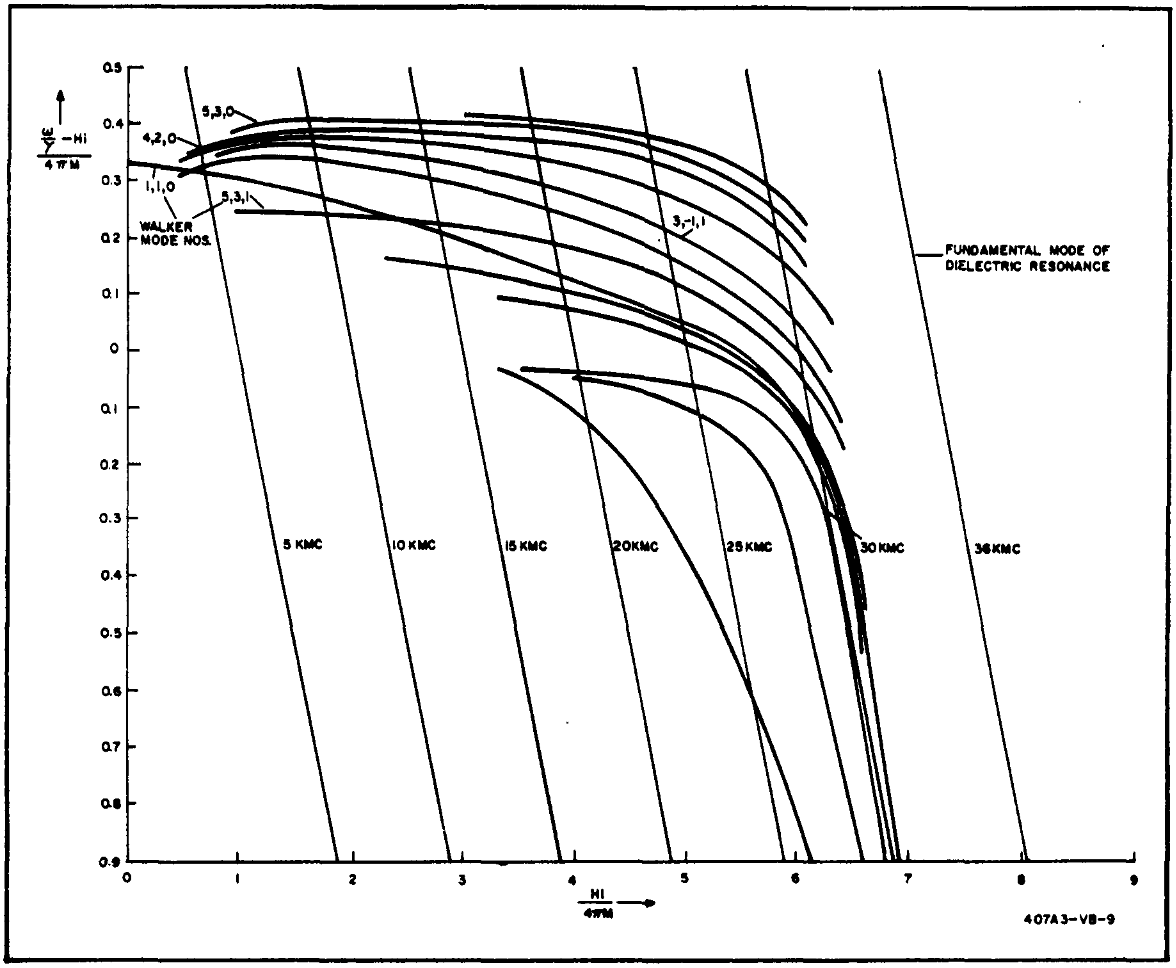

Figure 9. Magnetodynamic Mode Chart

with (P) being complex and j_n and h_n Bessel functions for a spherical geometry. The analysis showed that the n = 0 modes are totally damped; thus the lowest order are the n = 1 case where P was found to be approximately 0.755 + i 0.182. This value of P corresponds to a frequency of about 36 kilomegacycles which is near the center of the extended magnetodynamic mode dispersion shown on the chart.

This study has been valuable in showing the feasibility or requirements on properties measurements at some frequencies, such as those at or near mode crossings. For example, the most successful techniques for measuring ferrimagnetic susceptibility depend upon the perturbation of a cavity resonance by ferrimagnetic resonance. The chart has shown that at frequencies at which some of these measurements were unsuccessful there have been higher order modes close enough to take part in the perturbation and thus invalidate the measurement. The chart also explains wide variations in linewidth displayed in past reports as being direct functions of the proximity of higher order modes. In previous attempts to measure linewidth, it was assumed that the uniform precessional mode would always be the mode that caused the greatest interaction and thus be identified. This study has shown that while the uniform mode interaction decreases near dielectric resonance, that of some higher order modes increases, thus, explaining discontinuities in previous linewidth plots as being caused by unknowingly shifting from the uniform precessional to some other mode. The accuracy of the ferrite properties measurements has therefore been greatly increased as the experimenter can follow the chart point by point if necessary to facilitate his measurement.

5. CONCLUSIONS

Experimental correlation has been achieved for the 8-mm data, $H < H_o$, on rods composed of R-1 ferrite material ground to 100-mil, 125-mil, and 150-mil diameters and inserted across the narrow dimension of K_a-band waveguide. New data have been obtained for 8 mm and 2 mm which has permitted demonstration of the choice of an operating point. The circumferentially symmetric longitudinal $(0(S_1), 1)$ mode was used for the pump mode. The oppositely rotating circularly polarized $(\pm 1, 1)$ modes have tranverse field components suitable for signal and idler operation.

Work has begun on the dielectric rod structure as an alternate magnetodynamic resonant structure capable of supporting a parametric interaction. A typical operating point has been worked out on the basis of dispersive data in which the H_{01} mode would support the pump and the HE_{11} mode either the signal or idler, the other being supported by the uniform precessional mode.

Charting of the magnetodynamic mode spectrum of a spherical YIG resonator over a wide frequency range has permitted close correlation with the theoretical Walker mode spectrum at low frequencies and good agreement with predicted modes of the dielectric sphere resonator at high frequencies. For the 80-mil sphere, electromagnetic propagation effects appear to become appreciable at about 6 kilomegacycles. This study will ensure identification of modes, thus augmenting the ferrimagnetic measurements capability.

6. WORK FOR NEXT PERIOD

The ferrimagnetic rod resonant structure was analyzed and limited dispersive data were computed to investigate the modal structure. Techniques have been developed which permit establishing simultaneous resonance in modes appropriately related for amplification. In the following period, very large narrow linewidth single crystals will be procured. Techniques for shaping and polishing these crystals to suitable shapes will be investigated. As the traveling-wave study suggests an appropriate parametric operating point, dispersive data will be computed to permit design of a suitable resonant structure.

Work on the dielectric rod structure will proceed by the construction of a structure along the dimension suggested in the report. Excitation techniques will be investigated for pump and signal modes. As soon as suitable feed techniques are developed, attempts will be made to obtain a parametric interaction.

The study of traveling-wave parametric amplification will proceed by way of further investigation of operation with the signal (or idler) at gyromagnetic resonance. A structural cross section whereby the ferrimagnetic material occupies only a portion of the transmission cross section will be utilized to permit use of a perturbation technique and simplify the analysis.

7. IDENTIFICATION OF PERSONNEL

7.1 PERSONNEL

Name	Title	Hours
Robert A. Moore	Project Manager	212
Denis C. Webb	Associate Engineer	176
John D. Cowlishaw	Associate Engineer	328
Philip L. Noel	Assistant Engineer	144

7.2 BIOGRAPHIES OF PERSONNEL

PHILIP L. NOEL - Mr. Noel entered Northeastern University in 1957 and received his B.S.E.E. in June 1962. Both while in school on cooperative work assignment and since graduation he has worked in the Applied Physics Group where he has worked on the development of wideband parametric amplifiers using both varactors and ferrite as the coupling element, parametric amplifier noise figure studies, ferrite properties measurements, including linewidth, and susceptibility. He is presently conducting a study of propagation effects on ferrimagnetic materials.

Mr. Noel is a member of Eta Kappa Nu Association, the American Institute of Electrical Engineers, and the Institute of Radio Engineers.

The other biographies were given in Quarterly Report No. 6.

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Per telecon w/Dr Auer this date (9 Feb 63)
this report is unclassified

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U.S. Army Signal Research and Development Agency, Fort Monmouth, New Jersey. RESEARCH ON MILLIMETER FERROMAGNETIC TYPE PARAMETRIC AMPLIFIER. Quarterly Progress Report No. 3, January 1963, 31 pages including illustrations and tables.

Unclassified Report

In previous reports, the dispersion of four of the modes of the longitudinally magnetized ferrimagnetic rod has been presented for 8 mm and 4 mm, and $H < H_o$, where H_o is the magnetic field for gyromagnetic resonance. In this period, fairly good experimental correlation was obtained for the 8-mm data. In addition, new data have been obtained for 2 mm, $H < H_o$, and for 8 mm $H > H_o$. A method for establishing an operating point is described. As an example, a rod size is shown which will support three appropriately chosen simultaneous electromagnetic resonances.

Work has begun on the dielectric rod structure as a means of treating the more difficult case of the ferrite rod. For example, similar feeds are required for analogous modes.

(over)

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1. Ferromagnetic parametric amplifier
2. Millimeter wavelength
3. Ferromagnetic rod
4. Electromagnetic resonator
5. Dielectric rod
6. Ferromagnetism

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Analysis of the dispersive properties is much simpler and is available from a number of previous studies. An operating point is chosen from a knowledge of the dispersive behavior of the dielectric rod.

The magnetodynamic mode chart discussed in the two previous reports is substantially completed. Charting over a wide frequency range has permitted close correlation with the theoretical Walker mode spectrum at low frequencies and good agreement with predicted modes of the dielectric sphere resonator at high frequencies. This will allow positive mode identification, thereby augmenting the ferrimagnetic measurements capability.

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